AFRL-AFOSR-JP-TR-2016-0093

Development of Component Mechanisms and Novel Actuation for Origami Inspired Designs

Kyu-Jin Cho
SEOUL NATIONAL UNIVERSITY

11/17/2016
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ IOA
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
21-11-2016

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
20 Aug 2013 to 19 Aug 2016

4. TITLE AND SUBTITLE
Development of Component Mechanisms and Novel Actuation for Origami Inspired Designs

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA2386-13-1-4019

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Kyu-Jin Cho

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
SEOUL NATIONAL UNIVERSITY
SNUR&DB FOUNDATION RESEARCH PARK CENTER
SEOUL, 151742 KR

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AOARD
UNIT 45002
APO AP 96338-5002

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR IOA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-JP-TR-2016-0093

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
We propose to design and implement novel origami-inspired mechanisms that are embedded with actuators. The key research goal is to contribute to establishing fundamental design components that can be used to develop various active engineering systems inspired by origami designs, and provide concrete demonstrations of how origami designs can be exploited to provide a scalable mechanism that can function as a useful active system, not just a structure. To achieve the goal, we tried to develop multilateral topics related to origami-inspired mechanisms which includes pattern design as well as fabrication and actuation. We suggest novel design methods that solve specific design requirement, but our theme and design methodology can be applied as design component to various applications.
The research has three main thrusts:
1. Innovative design and fabrication of origami-inspired functional mechanisms.
2. Novel embedded actuation system for origami-inspired mechanisms
3. Integration of the developed mechanisms and actuation to practical application

15. SUBJECT TERMS
AOARD, Origami, Multi-functional structures

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
Unclassified	Unclassified	Unclassified	SAR	18

19a. NAME OF RESPONSIBLE PERSON
ROBERTSON, SCOTT

19b. TELEPHONE NUMBER *(Include area code)*
+81-042-511-7008

Final Report for AOARD Grant FA2386-13-1-4019

"Development of component mechanisms and novel actuation for origami inspired designs"

Date: 2016.11.14

Name of Principal Investigators (PI and Co-PIs):
- e-mail address : kjcho@snu.ac.kr
- Institution : Seoul National University, Korea
- Mailing Address : Rm. 402, Bldg. 312, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul, Republic of Korea
- Phone : +82–2–880–1663
- Fax : N/A

Period of Performance: Aug/20/2013 – Aug/19/2016

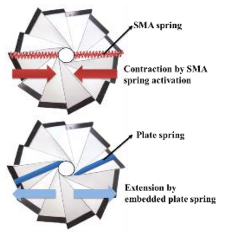
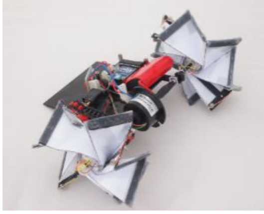
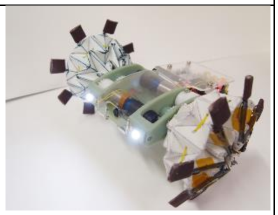
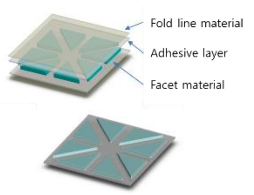
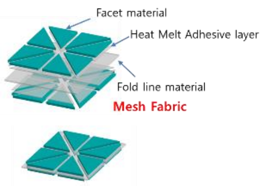
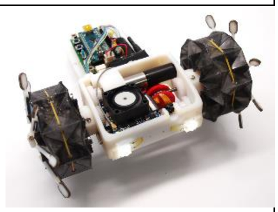
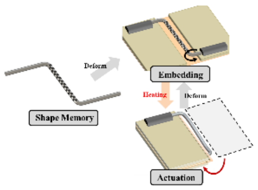
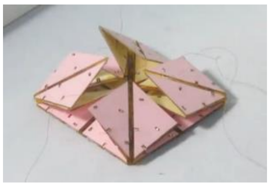
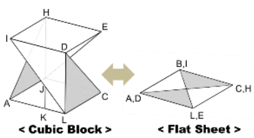
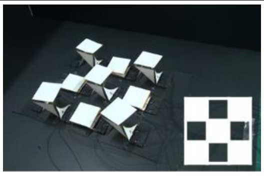
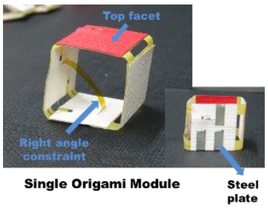
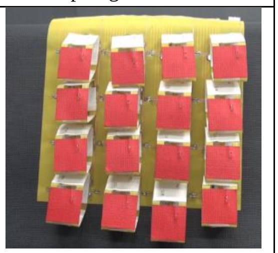
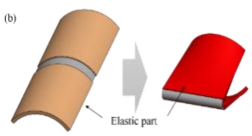
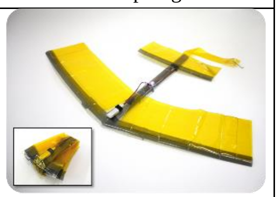
I. Project Summary:

We propose to design and implement novel origami-inspired mechanisms that are embedded with actuators. The key research goal is to contribute to establishing fundamental design components that can be used to develop various active engineering systems inspired by origami designs, and provide concrete demonstrations of how origami designs can be exploited to provide a scalable mechanism that can function as a useful active system, not just a structure. To achieve the goal, we tried to develop multilateral topics related to origami-inspired mechanisms which includes pattern design as well as fabrication and actuation. We suggest novel design methods that solve specific design requirement, but our theme and design methodology can be applied as design component to various applications.

The research has three main thrusts:
1. Innovative design and fabrication of origami-inspired functional mechanisms.
2. Novel embedded actuation system for origami-inspired mechanisms
3. Integration of the developed mechanisms and actuation to practical application

In the first year, we presented novel design techniques related to two applications – origami based deformable wheel and origami based self-folding sheet. The suggested techniques of each topic utilized the advantages of origami concept and also show unique characteristics. In the second year, we had tried to improve both concepts. For the deformable wheel, we conducted a comprehensive kinematic analysis on the wheel structure. Based on the result, we improved the wheel performance by introducing the hybrid origami patterning method. For the self-folding origami sheet, we tried new shape changing concept which combines a modular concept with an origami concept. The modularized approach enables to build shape-shifting system more easily. In the third year, we had tried to verify the performance of each concept and also expand the application field of the developed mechanism. Origami-inspired wheel mechanism developed from this project was applied to SNUMAX, the soft robot for the competition *'RoboSoft Grand Challenge 2016'*, and contributed greatly to SNUMAX's winning performance. Table 1 summarizes the component technologies developed from the project.

Table 1. Component technologies developed from the project

Name	Representative Figure	Brief Explanation	Application
Deformable wheel structure based on space sail pattern		The whole structure is linked so that the structure always maintain circular shape while the diameter is varied. The origami pattern constraint the unnecessary deformation without diameter changing.	 Deformable Wheel ver. 2
Deformable wheel structure based on waterbomb pattern		The deformable wheel based on waterbomb tessellation pattern enables more efficient deformation mechanism. The actuation force is proportional to payload which make it possible to increase the payload.	 Deformable Wheel ver. 5
Pattern embedded composite fabrication		Building an origami structure using multi-material can increase the robustness of the structure. By overlapping patterned rigid facet with flexible material, we solved delamination problem.	 SNUMAX
Patterned composite with mesh fabric fabrication		To increase the adhesive force, mesh fabric is used for the fold line material. The thermal adhesive permeates the mesh, which reinforces its adhesive strength.	 Deformable Wheel ver. 6
Torsional SMA actuator		A torsion shape-memory alloy (SMA) wire actuator embedded in origami structures that actively folds the origami A simple wire is aligned with the fold line, and each end is fixed to a facet. The twisting of the wire directly rotates the facets.	 Self-Folding Sheet
Bistable morphing voxel structure		Self-folding origami modules that transform from a cubic to a flat shape similarly to a voxel using a low-profile torsional SMA wire actuator. The module has bi-stability so that it can maintain its shape without actuator force.	 Morphing Voxel Sheet
Modular morphing voxel structure		To improve the simplicity of the system, morphing voxel as sticker type was built, by separating the system hardware into two different functional part - morphing voxel as an actuation unit and the base layer as an infrastructure.	 Modular Mophing Voxel
Curved compliant facet origami		A curved compliant origami structure by utilizing the compliance of the material, and an application of the structure for a jump-gliding multimodal robot.	 Self-Depolyable Glider

II. Research Performances:

1. Origami based kinetic structure - Deformable wheel

In origami structure, each fold line and vertex can be regarded as mechanical components, e.g., linkages and joints. Using the same token, origami itself could be a combined structure of the mechanical components. Through analysis of the fold lines, origami structures can be developed to function like a real mechanical system. The research in this chapter focus on this characteristic - origami structure is morphing structure, but it is kinematically designable and can be used as a mechanical system.

In this research, we had proposed a novel variable-diameter wheel using an origami-based soft robotics design approach. Using soft materials for a variable-diameter wheel accompanies two advantages – high deformability and ability to absorb impact, but inadequate stiffness and excessive degrees of freedom can impede a wheel's functionality. Our key idea is to overcome these deficiencies by patterning a rigid material on a soft material like origami. We can construct a structure with flexible regions (folding parts) that provide high deformability and rigid regions (facets) that regulate excessive degrees of freedom and increase stiffness, for improved functionality.

The proposed design provides three key advantages. First, the structure can be built without lots of mechanical parts or a complex assembly process. A single sheet replaces most parts, and a folding part generates each joint. This reduces not only the fabrication cost for each part but also the time required for assembly. Second, an origami structure can have high stiffness and impact capacity compared to its weight. In complex kinematic structures, the local distortion of links and joint alignments strongly affects how a structure moves. However, an origami structure is composed of compliant folding parts and facets, so the whole structure can perform as a shock absorber. Also, a specially organized origami structure such as a honeycomb greatly increases the effective stiffness of the whole structure. Third, an origami structure is scalable. The structure generates a joint by folding, and this reduces friction between the links. Finally, the simplified assembly process made possible by using origami structures reduces the difficulty of assembling small-scale parts.

1.1. Wheel pattern design

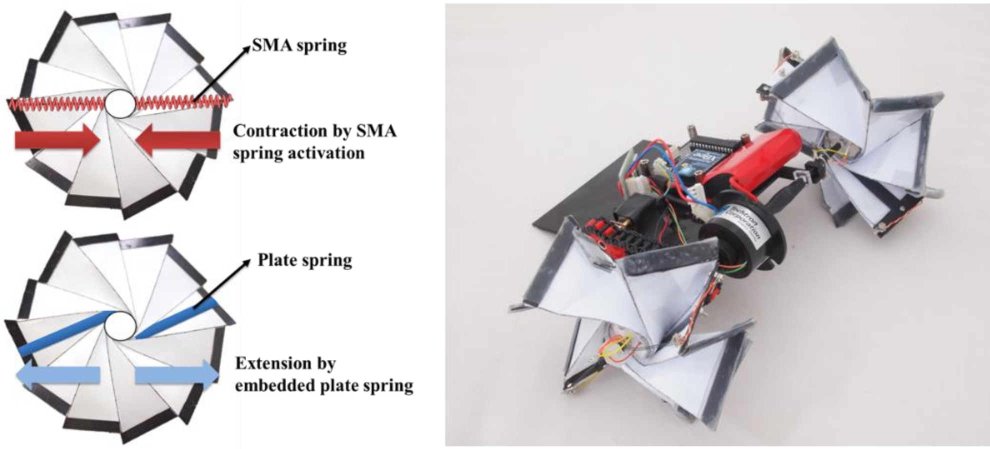


Fig. 2. Schematic of shape transformation mechanism (Left) and the robot prototype using the proposed diameter variable wheel (Right).

The origami structure was chosen which always maintain circular shape while the diameter is varied. The structure should have restricted degrees of freedom, thereby it constraint the unnecessary deformation without diameter changing. The origami model proposed by S. D. Guest et al, which was originally developed for folding inextensible space sail membrane can accomplish this functionality (Fig. 2).

This structure has two main advantages. First is the shape. All the segments of the wheel are linked together and enable the structure to maintain a circular shape independent of whether it is folded or not. This is one of the main reasons why this structure is selected to be used as a wheel. Second is the force transmissibility and the stiffness maintenance. A wheel that supports the whole body of the robot usually encounters a stiffness problem. Since whole wheel structure is linked together in this wheel, controlling the stiffness of every segment is not required. This reduces complexity of the system and increase power

efficiency in shape changing. However, the proposed structure has parallel force direction in payload and transformation. This cause a problem that the actuation force should be proportional to payload which make it difficult to increase the payload force.

Waterbomb tessellation pattern is proposed to solve this problem (Fig. 3). Tessellated sphere shaped waterbomb pattern was used for the wheel body (Fig. 3 (a) and (b)) and the outer sides of the pattern was modified (Fig. 3 (c)) to build a connecting structure between the wheel body and the wheel hub (Fig. 3 (d)). The wheel hub part maintain the wheel shape and also transmit the torque to the wheel body. Fig. 4 shows the assembled wheel structure.

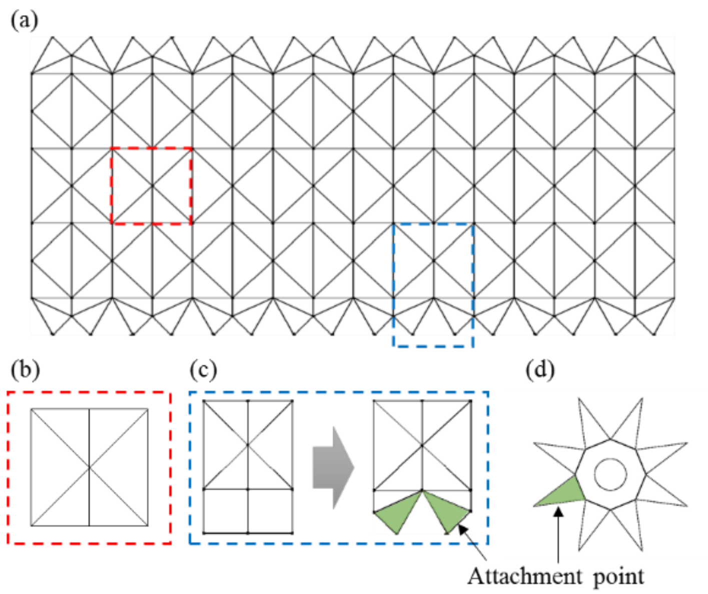


Fig. 3. Folding patterns for the wheel (a) Main body pattern (b) Unit pattern (c) Pattern variation for hub assembly (d) Wheel hub pattern.

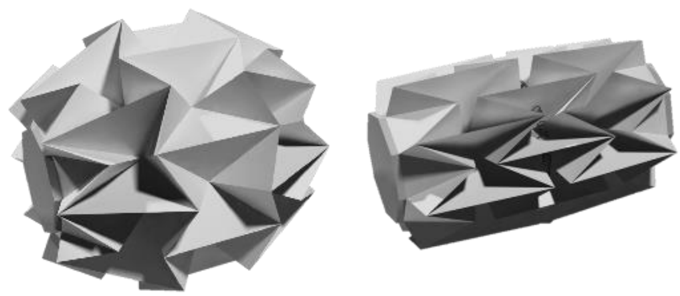


Fig. 4. Shape of origami wheel (left) Normal state (right) Shrunk state.

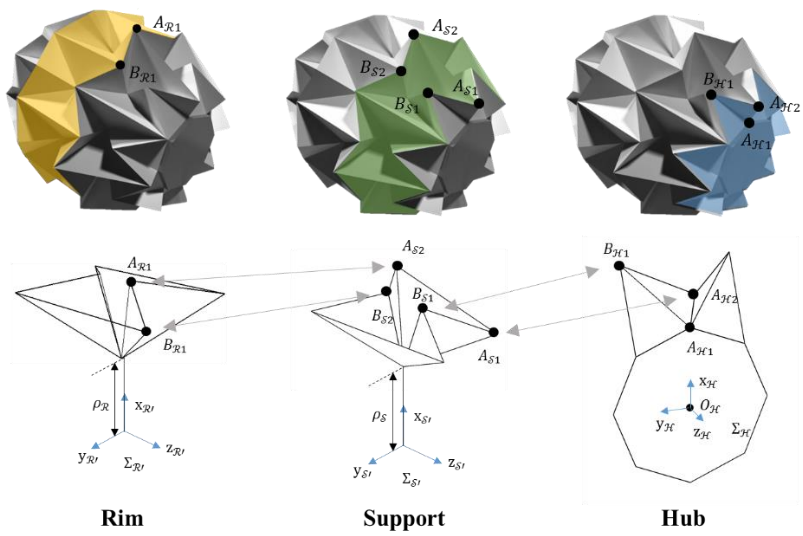


Fig.5. Components analysis of the wheel structure

Technically, the origami structure cannot follow ideal rigid body kinematics. A fold line cannot be an ideal line and should have a specific width. Also, facets may bend owing to compliance of the material from which the structure is made. In other words, the structure can move regardless of its kinematic mobility. Although the kinematics of the structure cannot perfectly constrain the structure, kinematic analysis is still important because kinematics determines the moving direction of the structure, and lack of kinematic mobility hinders movement.

Fig. 5 shows the wheel components. The wheel structure analysis was conducted in three steps. First, we specified the variables and derived the constraints from the geometry of each part. These variables and constraint equations determine the configuration of each part. Next, the symmetry constraints for maintaining the circular shape of the wheel were added. In last step, the constraints for assembling of each part were derived. Table 2 presents the variables and table 3 presents the constraint equations of the wheel structure.

Table 2. Variables determining wheel configuration

	Angle Variable	Position Variable
Wheel hub part	$\theta_{\mathcal{H}1},\ \theta_{\mathcal{H}2}$	$\eta_{\mathcal{H}}$
Wheel support part	$\theta_{\mathcal{S}1},\ \theta_{\mathcal{S}2},\ \theta_{\mathcal{S}3},\ \theta_{\mathcal{S}4}$	$\rho_{\mathcal{S}},\ \eta_{\mathcal{S}}$
Wheel rim part	$\theta_{\mathcal{R}1},\ \theta_{\mathcal{R}2}$	$\rho_{\mathcal{R}}$

Table 3. Constraints determining wheel configuration

Constraint of wheel hub part

$$\tan\frac{\pi}{n}\left(\frac{l_t\cos\theta_{\mathcal{H}1}+l_h}{l_u}+\sin\theta_{\mathcal{H}1}\sin\theta_{\mathcal{H}2}\right)-\cos\theta_{\mathcal{H}2}=0$$

Constraint of wheel support part

$$(\sin\theta_{\mathcal{S}2}+\sin\theta_{\mathcal{S}4})\sin(\theta_{\mathcal{S}1}+\theta_{\mathcal{S}3})+(1-\sin\theta_{\mathcal{S}2}\sin\theta_{\mathcal{S}4})\cos(\theta_{\mathcal{S}1}+\theta_{\mathcal{S}3})-\cos\theta_{\mathcal{S}2}\cos\theta_{\mathcal{S}4}=0$$

$$(\rho_{\mathcal{S}}+l_u(\sin\theta_{\mathcal{S}1}-\cos\theta_{\mathcal{S}1}\sin\theta_{\mathcal{S}2}))\tan\frac{\pi}{n}-l_u\cos\theta_{\mathcal{S}2}=0$$

$$(\rho_{\mathcal{S}}+l_u(\sin\theta_{\mathcal{S}3}-\cos\theta_{\mathcal{S}3}\sin\theta_{\mathcal{S}4}))\tan\frac{\pi}{n}-l_u\cos\theta_{\mathcal{S}4}=0$$

Constraint of wheel rim part

$$(\cos\theta_{\mathcal{R}1}+\sin\theta_{\mathcal{R}1}\sin\theta_{\mathcal{R}2})=1$$

$$(\rho_{\mathcal{R}}+l_u(\sin\theta_{\mathcal{R}1}-\cos\theta_{\mathcal{R}1}\sin\theta_{\mathcal{R}2}))\tan\frac{\pi}{n}-l_u\cos\theta_{\mathcal{R}2}=0$$

Constraint of hub support part assembly

$$l_u\cos\theta_{\mathcal{S}2}/\sin\frac{\pi}{n}-l_h+l_t\cos\theta_{\mathcal{H}1}=0$$

$$\eta_{\mathcal{S}}+l_u\cos\theta_{\mathcal{S}1}+l_u\sin\theta_{\mathcal{S}1}\sin\theta_{\mathcal{S}2}-(\eta_{\mathcal{H}}+l_t\sin\theta_{\mathcal{H}1})=0$$

$$\rho_{\mathcal{S}}+l_u\sin\theta_{\mathcal{S}1}-l_u\cos\theta_{\mathcal{H}2}/\sin\frac{\pi}{n}=0$$

Constraint of support – rim part assembly

$$\rho_{\mathcal{R}}+l_u\sin\theta_{\mathcal{R}1}-l_u\cos\theta_{\mathcal{S}4}/\sin\frac{\pi}{n}=0$$

$$l_u\cos\theta_{\mathcal{R}2}/\sin\frac{\pi}{n}-(\rho_{\mathcal{S}}+l_u\sin\theta_{\mathcal{S}3})=0$$

$$l_u\cos\theta_{\mathcal{R}1}+l_u\sin\theta_{\mathcal{R}1}\sin\theta_{\mathcal{R}2}-(\eta_{\mathcal{S}}-l_u\cos\theta_{\mathcal{S}3})=0$$

The proposed structure has an equal number of variables with constraint equations, which leads to zero mobility of the mechanism. This problem can be solved by cutting the material, but that would seriously weaken the structure’s robustness. Our solution to this problem is releasing the constraints by using a flexible facet in a specific region. This is simply achieved by increasing the area of the folding part. A small width of the folding part constrains most of the movement of the adjacent facets without revolute joint motion. However, increasing the area of the folding part to a level of the facet allows for much more flexible movement so that the adjacent facets gain extra degrees of freedom. This hybrid design approach—utilizing both rigid and flexible facets—allows high design flexibility (Fig. 6, 7).

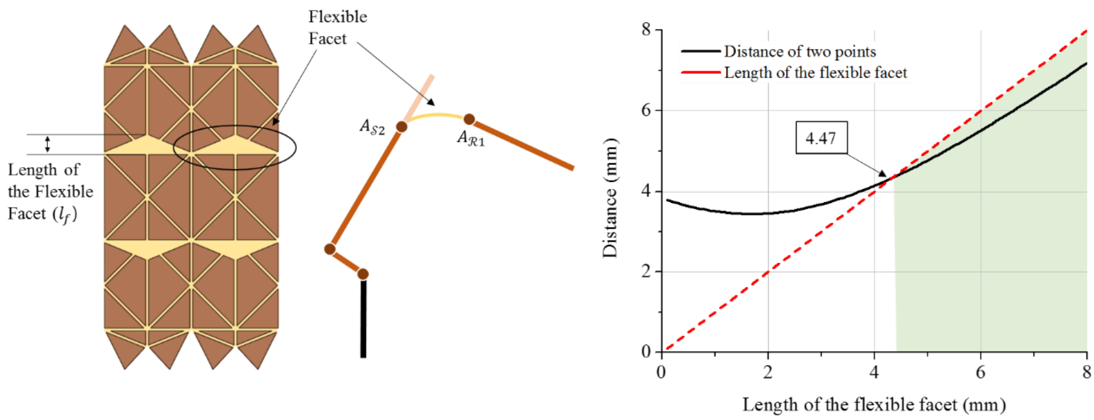


Fig. 6. Schematic and tendency of the flexible facet. Tendency of maximum distance to vary as length of the flexible facet increases. A value of 4.47 mm of the length of the flexible facet (about 18% of the length of the unit pattern), has been chosen.

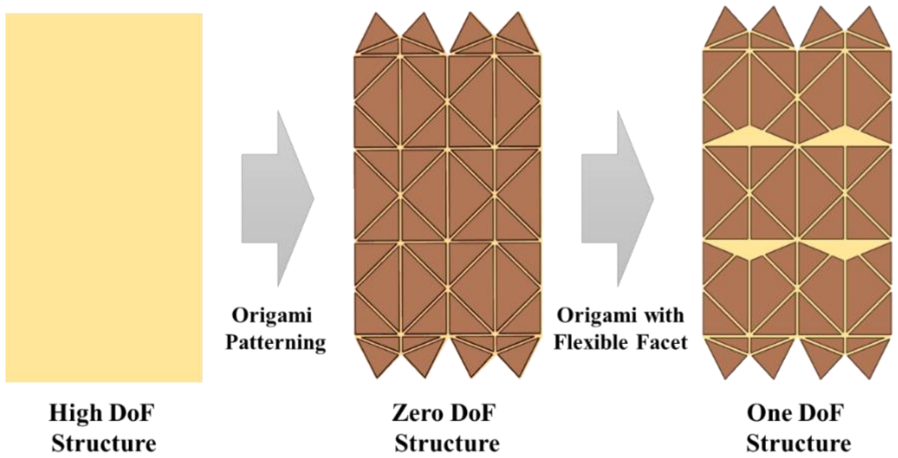


Fig. 7. Design summary of variable-diameter wheel pattern. The patterning on the flexible material overly constrains movement, but adding flexible facets adjusts the degrees of freedom

1.2. Fabrication of foldable structure

Depending on the material and the fabrication method, the properties of final origami structure are determined. Therefore, to realize desired functionality of final origami structure, we should select appropriate fabrication method as well as properly designed origami pattern.

In this research, we presented new origami fabrication method for improving the desired functionality of final origami structure. By using multi-material to differentiate material property between fold lines and facets, we can achieve low resistance in actuation, secure the structural durability and control the stiffness of the structure at the same time. Also, because the new composite is nothing but layering of 2-D manufactured substrates, it still has advantages of 2-D fabrication, and by embedding the facet pieces between flexible materials, the final structure is free of peeling and tearing (Fig. 8).

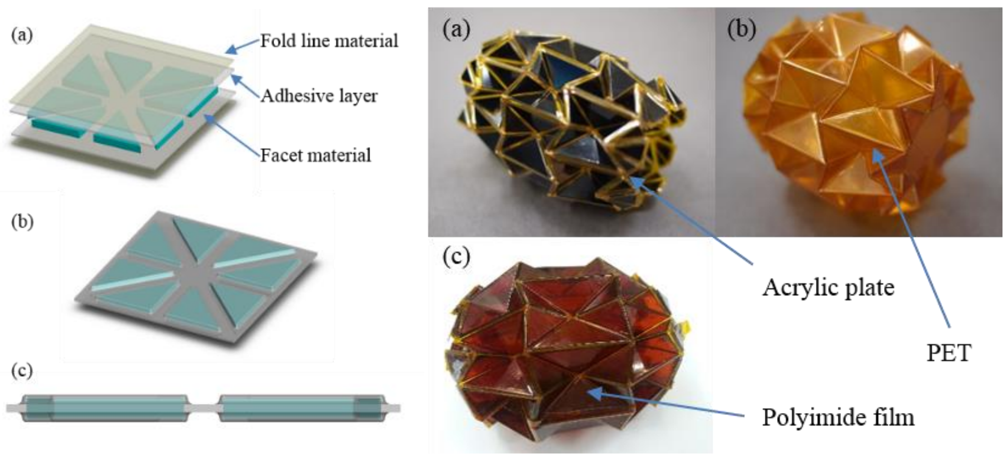


Fig. 8. Fabrication of pattern embedded composite. Various planar material can be used

1.3. Robot Design

The wheel deformation requires the movement of the shaft structure. To reduce the required internal space, we replaced the rigid shaft with a flexible one. The flexible shaft is connected to the outside hub via a bearing, so the shaft can pull the outside hub when the shaft pulley winds it up (Fig. 9 [a]). To ensure low resistance force during winding, a material with low bending stiffness is preferred. However, a low-stiffness material is susceptible to twisting because the wheel should be rotating.

To solve the problem, we used an anisotropic structure that has low bending stiffness and high torsional stiffness: a coil spring with a wire in its center. Coil springs have low bending stiffness and relatively high torsional stiffness, so the shaft can be wound up on the pulley without twisting. The wire prevents extension of the coil spring. The elastic band encircles the wheel to recover the original shape when the shaft tension is released.

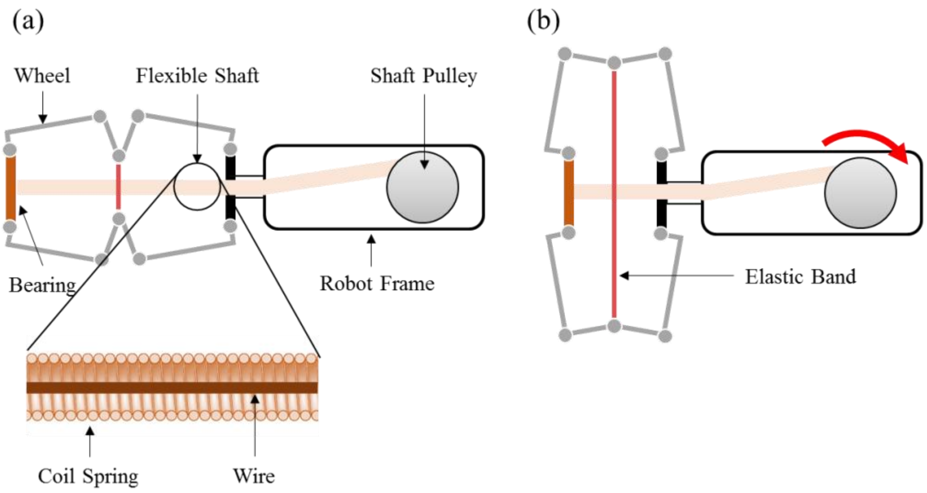


Fig. 9. Schematic of the wheel deformation mechanism using a flexible shaft. The coil spring allows the shaft to be wound up on the pulley and prevents twisting. The internal wire prevents extension of the coil spring.

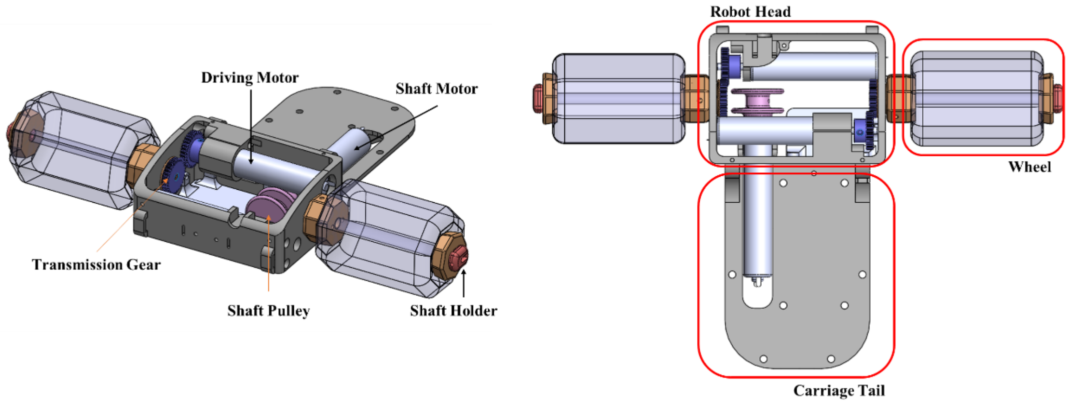


Fig. 10. Overall view of the wheel deformation and torque transmission mechanisms.

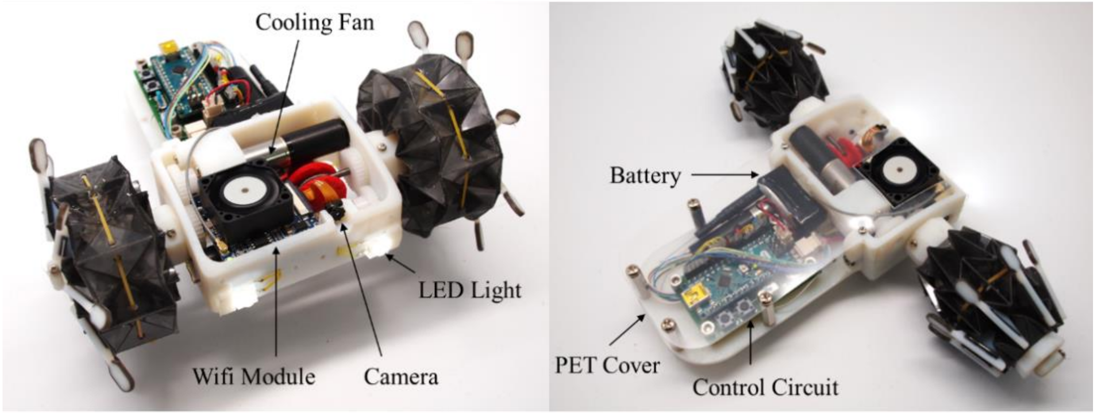


Fig. 11. Final assembled robot.

DISTRIBUTION A. Approved for public release: distribution unlimited.

All structural components of the robot were fabricated with a 3D printer. The communication module, cooling fan, and battery for the controller were placed on the head side, and the main controller and battery for the motors were placed on the carriage tail (Fig. 10 and 11). A PET cover was placed on the robot body to protect body components. The final robot weighs 278 g with batteries.

1.4. Performance evaluation

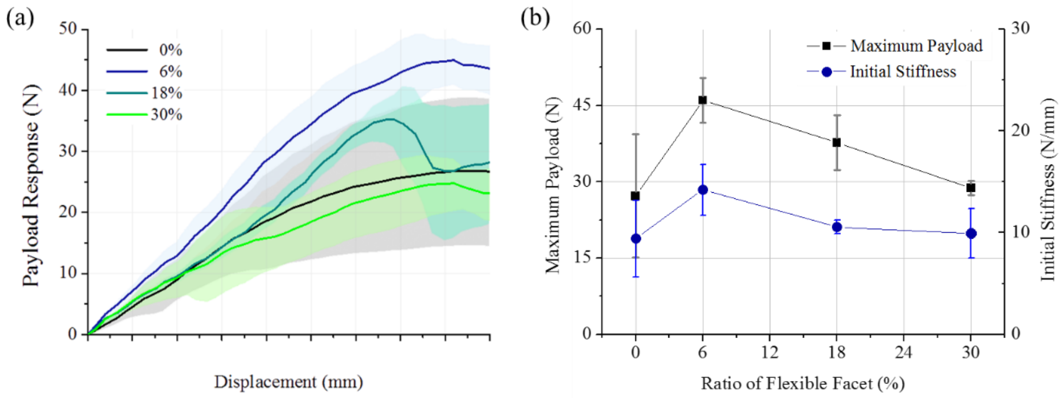


Fig.12. Experimental results of the wheel payload test. The graph (a) shows the force-displacement profile for the wheel payload response, and the graph (b) shows the maximum payload with initial stiffness (in 5% linearity).

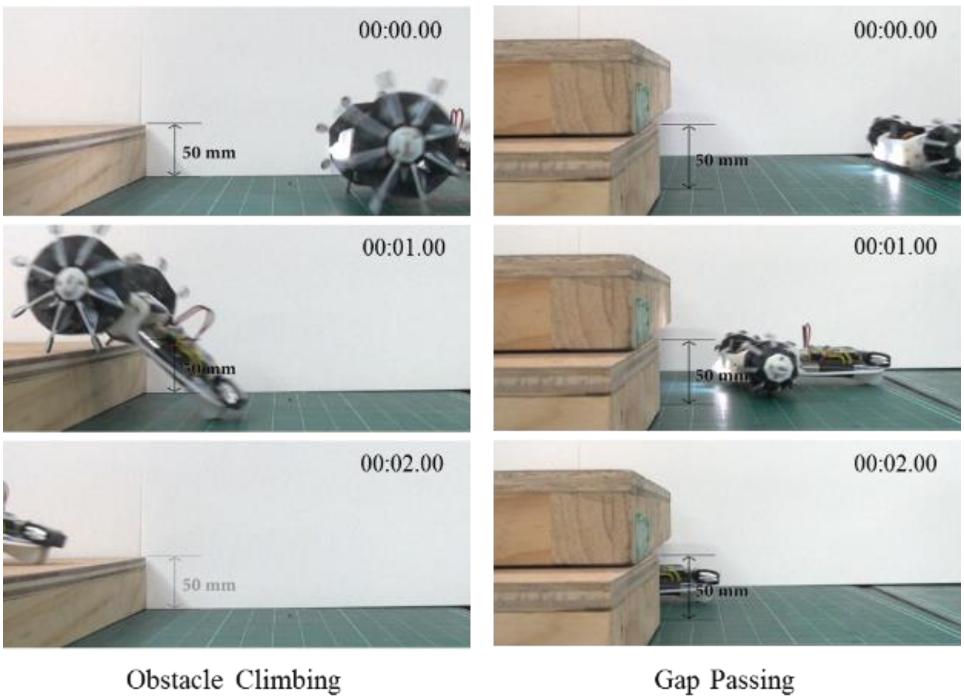


Fig. 13. Video snapshots of the maneuverability performance test.

Although the mechanism can move with zero kinematic mobility because of the compliance of the materials, the effect of the flexible facet on wheel performance is considerable. For the experiments, six types of specimens with different ratios of the flexible facet (0, 6, 12, 18, 24, 30%) were prepared. The weight of the specimens are about 9.7 g and can change its diameter from 30 mm to 68 mm.

Fig. 12 shows the results of the payload test. The bars present ±1 standard deviation. The maximum payload was measured at the point when the wheel supports collapsed. As the length of the flexible facet increases, the wheel become stable and maximum payload and initial stiffness also become high, but beyond a certain length a large flexible facet cannot hold the structure, and it collapses easily. In the robot, 18% of the flexible facets are used, which shows about 41 N of the maximum payload, which is more than 400 times the weight of the wheel structure.

Fig. 13 shows frames from a videotape of the robot with variable diameter wheel navigating the obstacles. By alternating the wheel diameter between these two states, the robot can climb a 50 mm step and pass over a 50 mm gap.

2. Origami embedded actuation system – Self folding origami morphing voxel

Origami is one efficient and simple way to build transformable structure by pattern design due to its inherent two-dimensional template, and motion generation principle on local hinge deformation. This origami based design is one possible solution to overcome the current modular-based approach to build physical programmable matter which dynamically changes its shape. One of the biggest challenges of origami design for programmable matter, is the complexity of geometrical relationships between folding units requires complex pattern generation and folding sequence to build diverse 3D shapes from all connected two-dimensional material. To solve this problem, we suggest new method exploits both the modular and the folding approach, distributed origami morphing voxel system (Fig. 14), which generates by integration of arranged transforming unit—morphing voxels which is a transforming unit that can vary between cubic block and flat sheet shapes. Mobility of the system is generated by each of the voxel's transformation, so that we can build programmable hardware by arranging the morphing voxels.

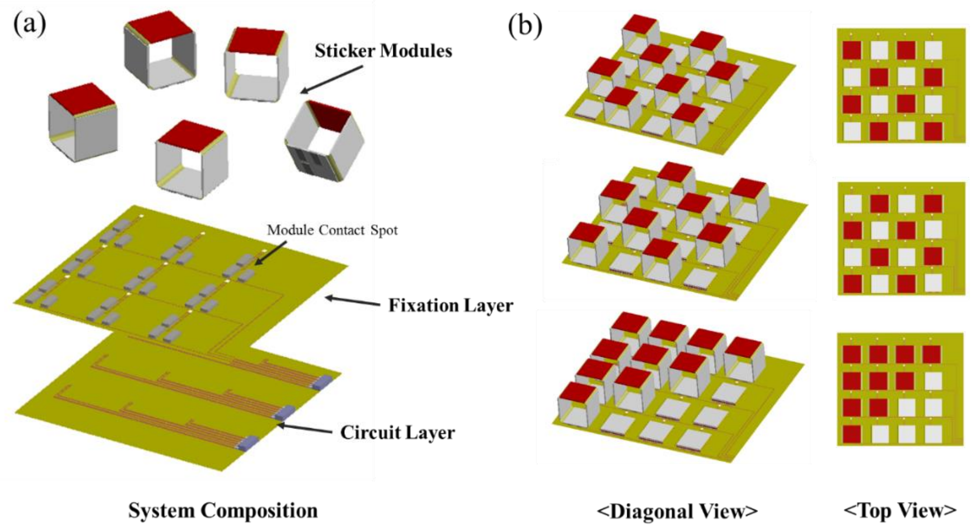


Fig. 14. Physical programmable matter system composed of distributed origami pop-up cells (a) front view (b) side view

The research in this chapter focuses on simple transformable unit—morphing voxel—design. In particular, key characteristics (e.g. range of motion, degrees of freedom) of an active origami structure are mainly determined by its pattern. Therefore we designed proper pattern satisfying following requirements for efficient and simple transformation:

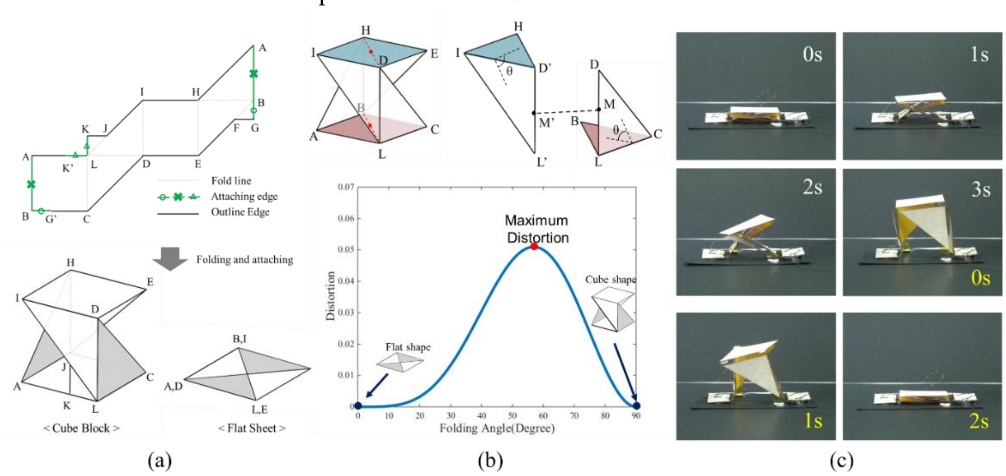


Fig. 15. Morphing voxel (a) origami pattern (b) geometrical analysis (c) transformation performance

1) The origami module should be capable of efficiently transform its shape from a flat sheet to cubic block and *vice versa*, with 1-DOF movement.
2) The transformation of the structural shape should be achieved by simple and minimum number of actuators for compactness.
3) The module can maintain the desired shape without additional force after transformation, to improve the energy-efficiency of the whole system.

To satisfy these design requirements, we designed origami module pattern based on Kresling pattern and applied Kirigami principle for simple morphing voxel, deploying like single DOF motion as illustrated in Fig. 15 (a). It is more compact and efficient method of transformation rather than traditional sequential folding of origami manufacturing for simplicity of actuation. Actually, this structure has zero DOF motion theoretically when we assume the facet is rigid material and the fold line is complete rotational joint. However, due to its structural characteristic it can deploy like 1 DOF structure having little distortion. By geometrical analysis, we plotted the distortion amount of the voxel during folding (Fig. 15 [b]), and determined the actuator design parameters for enough force. Also, due to the bi-stability of this pattern, a fully deployed cubic block shape and flat sheet shape can maintain their shapes without additional actuator force after deploying.

Fig. 15(c) shows the transformation performance of the single morphing voxel. We put 1A uniform current through power supply to the module actuators. It can transform its shape from flat to a cube within 3 seconds, 40 mm side length cubic block, and go back to a flat sheet within 2 seconds. Also, it can maintain its shape after transformation without additional force. Also, by arranging the morphing voxel into general matrix form, we made physical programmable matter system which can shift into 5 different configurations as illustrated in Fig. 16.

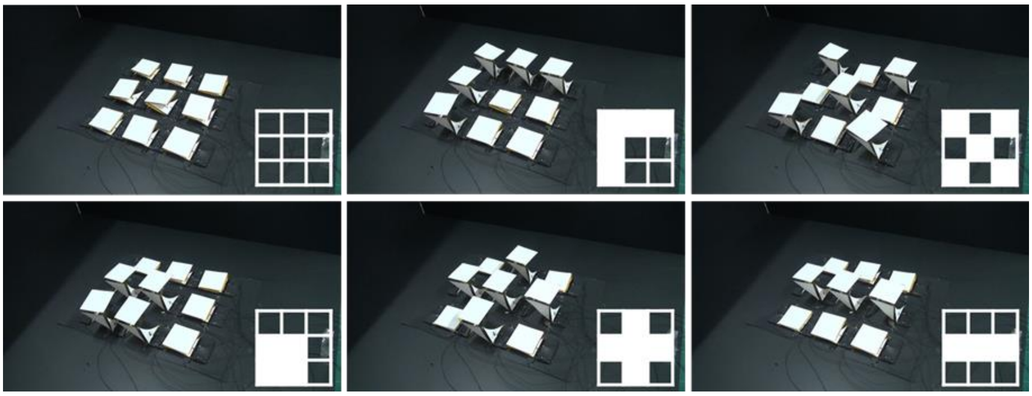


Fig. 16. Physical programmable matter with 3X3 matrix form of morphing voxels. From initial flat shape, it could transform its shape into 5 different shapes: gamma(Γ), X, square, plus(+), and minus(-) shape.

To improve the simplicity of the system, and overcome the limitations of morphing voxel on its location, we aim to build the morphing voxel as sticker type, by separating the system hardware into two different functional part, morphing voxel as an actuation unit and the base layer as an infrastructure. Morphing voxel is a transformable body embedded with the actuators and the electrodes for the supply of the control signal and power comes from the base layer. The base layer consist of fixation layer includes module contact point and circuit layer for the power and signal input to the cell for designating target configuration. Also, origami Pop-up cell and the base layer can be attached or detached through simple magnet contact. By separating the actuation unit and infrastructure, we give more freedom to the system in rearrangement, replacement, and repairing of the cell.

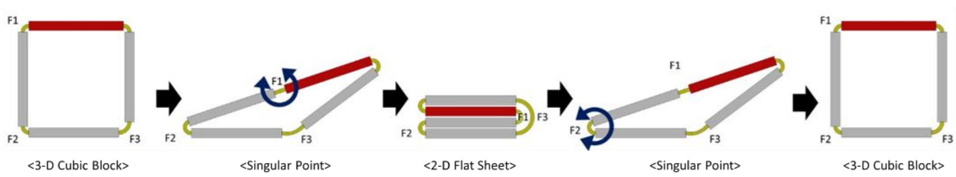


Fig. 17. Transformation process of four-bar linkage morphing voxel

Also, we changed the pattern as simpler origami pattern as four-sided structure with parallel fold-lines illustrated in Fig. 17. By using flexure joint as folding hinge, it can make large deformation movement with simple actuation. The flexure joints have high degrees of freedom, so calculating the specific position of the linkage based on the kinetic conditions requires a lot of computational cost. To understand the behavior of the structure more intuitively, we assumed that flexure joint always follows a circular arc which minimize the stored elastic energy in specific relative angle, and built a simple kinematic model based on the assumption. From this assumption, the effect of the flexure joint can be described as length variation of the linkage. We call it a virtual linkage. In other words, the structure with a flexure joint behaves like conventional four-bar linkage structure except the length of the linkage is changing. Using the virtual linkage, it is possible to formulate a kinematics of the flexure four-bar linkage. We determined the actuator direction and specification as the formulation based on virtual work theory.

As illustrated in Fig. 18, single cell has 30 mm side length, weighs 2.2 g, and takes average 3 to 4 seconds for single transformation. We put 0.8 A uniform current through power supply to the actuator, and switch the control sequence through electrodes in cell. As illustrated in Fig. 18 (c), (d), a single cell can transform its shape between 2-D flat sheet and 3-D cubic block after attached to the base layer.

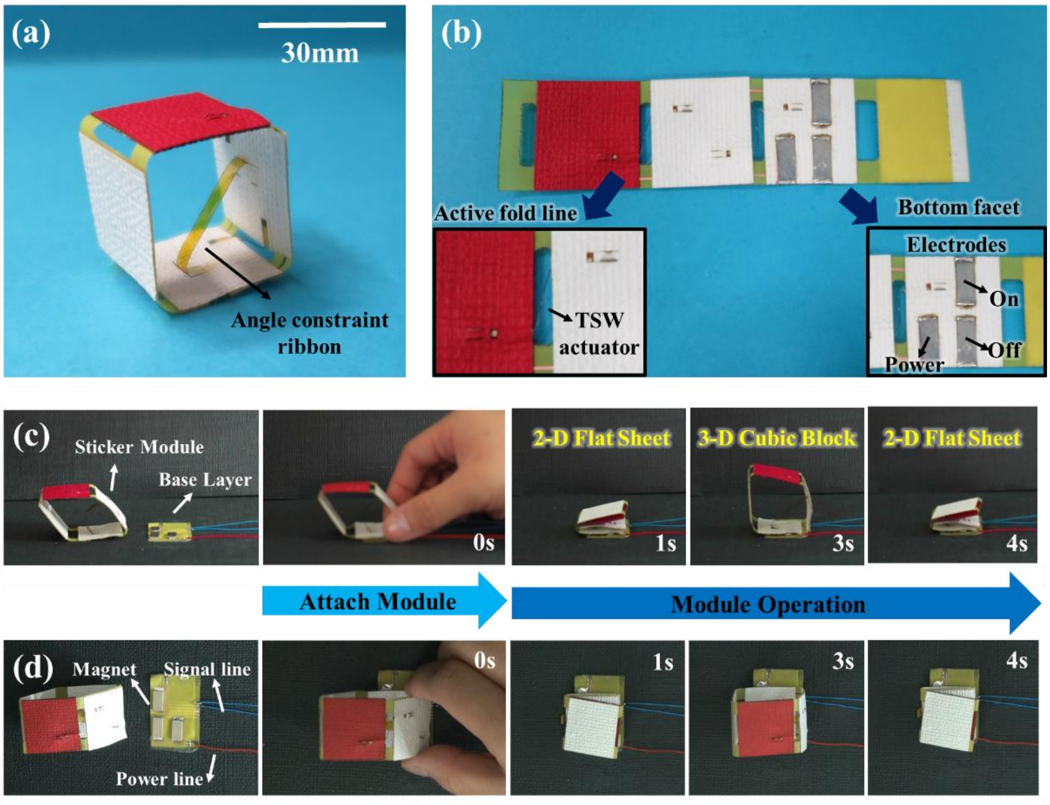


Fig. 18. Performance of the single Origami pop-up cell (a) Assembled cell (b) 2-D planar view of the Origami pop-up cell and its assembly, and transformation performance (c) side view (d) top view

This study suggest a new way to build physical programmable matter that is lightweight and have compact low-profile structure. By designing the distributed unit with self-folding dimensional variable unit, origami morphing voxel, we can build shape-changing hardware without complex control method.

3. Origami based energy storing mechanism – Self deployable glider

Origami structures are usually built with rigid facets and low-stiffness crease lines, and compliance and uncertainty about material properties are usually considered obstacles to be overcome when creating ideal origami-based designs. In this research, however, we focus on the benefits of using soft materials in origami structures. By utilizing the compliance of the material, we propose a curved compliant origami structure and an application of the structure for a jump-gliding multimodal robot (Fig. 19).

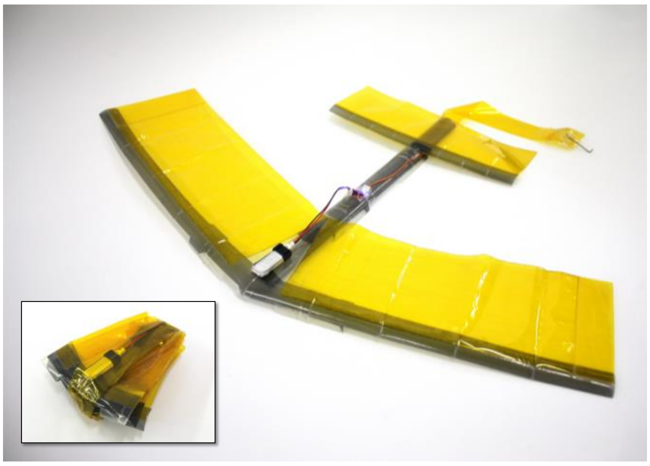


Fig. 19. Self-Deployable Gliding Wing Module.

3.1. Curved compliant facet origami

The glider wing should satisfy the following conditions: The wing should be fully foldable without plastic deformation to reduce drag at takeoff, rapidly deployable, and able to hold the robot's weight and endure aerodynamic forces during gliding. Moreover, a lightweight structure is recommended to reduce hindrances to jumping performance. In short, the wing requires higher stiffness and elastically fully foldability.

Using thicker fold-lines is a general method for increasing joint stiffness without changing the fold-line material. But this approach requires a wide fold-line that is fully foldable in the elastic region, which would make the origami structure bulky. So it is difficult to ensure both high joint stiffness and a low structure profile in a general flat origami structure. This limits the use of an origami structure for a foldable glider wing, which needs to be folded into a small area and requires high stiffness.

To overcome this limitation, we added longitudinal curvature to the facets of the origami structure to increase stiffness and keep a narrow fold-line. Unlike general origami, curved compliant facet origami distributes deformation not only to the fold-line but also to the curved facet (Fig. 20). The new origami structure acquires unique properties that make it suitable for use as a low-profile basic frame for the glider wing, without any other components. First, the structure is fully foldable and deploys itself. The curved compliant facet origami structure is composed of thin and highly flexible fold-lines and elastically curved facets. As we fold the structure, the curved facets of the structure gradually flatten. This elastic deformation of the facet makes the structure stable in the deployed state and also provides the force for deploying the folded structure.

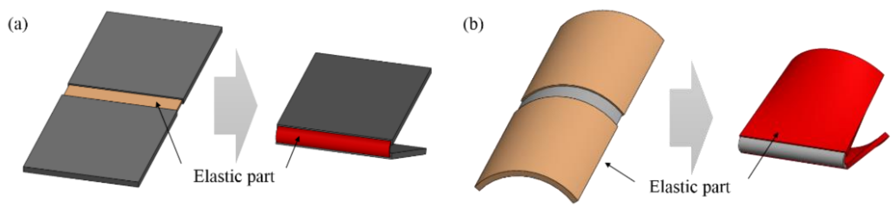


Fig. 20. Deformed region during folding. (a) In a general origami structure, deformation is concentrated on the fold-line. (b) In a curved compliant facet origami structure, deformation is distributed on the curved facet.

Second, the structure's joints have high stiffness in the deployed state, which prevents them from rotating in the deployed state. The joint has non-linear and anisotropic stiffness because of the initial longitudinal curvature, similar to the behavior of a tape spring. When a joint folds such that the concave sides of two curved facets approximate, this is termed equal-sense folding. When a joint folds such that the convex sides of two curved faces approximate, this is termed opposite-sense folding (Fig. 21). In the proposed origami structure, opposite-sense folding requires more force than equal-sense folding. By utilizing this characteristic, the basic frame for the wing can bear force in the opposite-sense direction to hold the wing in the deployed state during gliding.

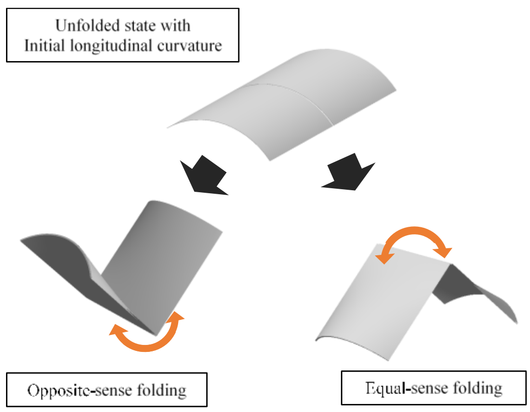


Fig. 21. Schematic figures of the two folding directions.

3.2. Fabrication of the Curved Compliant Facet Origami Structure

The facet material of the frame structure is PET film with a heat-adhesive layer (75 µm per side), and the fold-line material is meshed fabric (50 µm). The fabrication process follows two steps: Fabrication of the flat origami structure and then arching the flat structure.

In the first step, a fold-line pattern is engraved on the PET film via laser machining, and the mesh fabric is placed between two layers of the engraved film. The prepared material is laminated by applying heat and pressure via a heat roller. The laminated sheet is then cut along the outer line by laser machining. In the second step, the flat structure is conformed to an aluminum rod of the target curvature by wrapping, and heat is applied to slightly melt the PET. The structure is allowed to cool, at which point it is fixed in the target shape (Fig. 22).

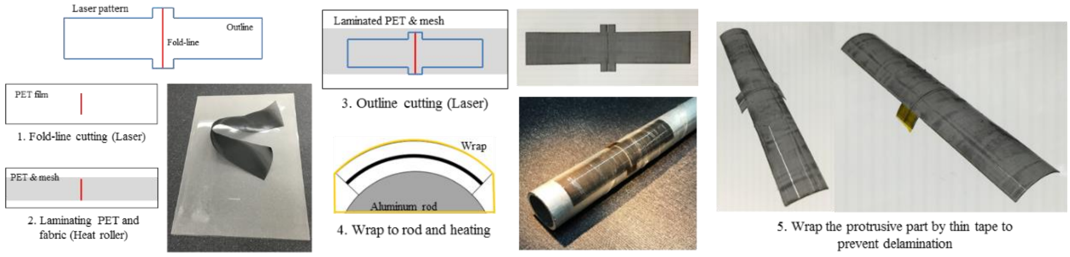


Fig. 22. Fabrication process for the curved compliant facet origami structure.

3.3. Self-Deployable Glider Design

The self-deployable gliding module is composed of a deploying frame, wings made of 25-µm Kapton film, and electronics for wireless triggering. The electronics include a battery, a controller (JF24AC 2.4-GHz receiver, 0.4 g) and a servo motor (PZ-15320A1, 1.88 g, 14 x 6.2 x 17.9 mm) (Fig. 23). Overall length is 30 cm, the main wing and tail wing spans are 44.7 cm and 20 cm respectively, and the total weight is 13.6 g without the electronics and 20.3 g with the electronics.

To reduce the area of the folded state, the main wing part, the tail wing part, and the backbone part are also folded. The whole structure can be folded to 1/8.1 of its deployed state area (from 610 cm^2 to 75 cm^2). The folding sequence follows three steps: Main wing folding, tail wing folding, and backbone folding.

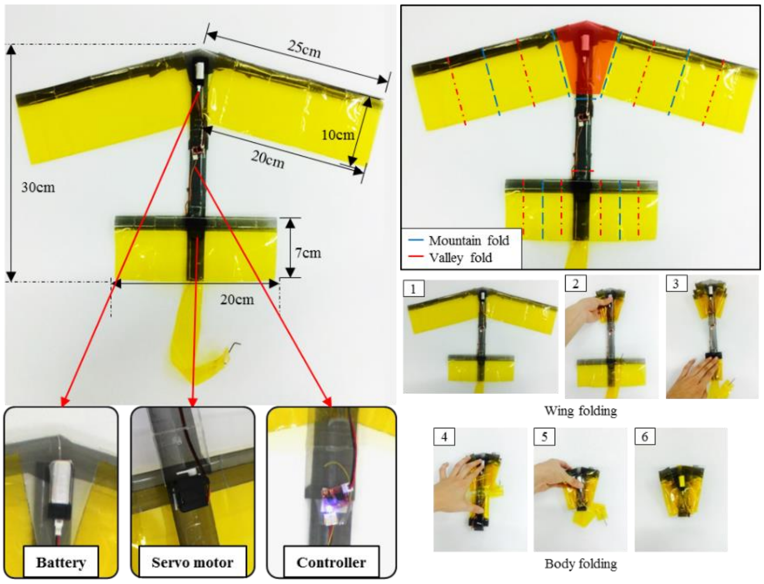
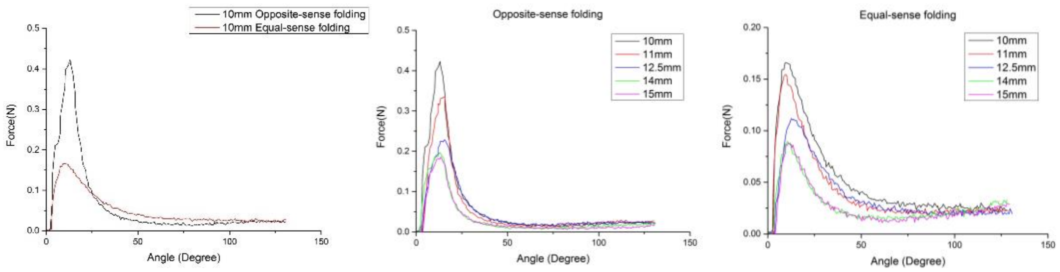


Fig. 23. Specifications of the self-deployable gliding wing module and folding methods.

3.4. Characteristics Test of the Curved Facet Origami Structure



(a) (b) (c)

Fig. 24. (a) Experimental data of the curved compliant facet origami structure for a 10-mm radius of curvature. Force profile comparison between folding directions: (b) force profile for opposite-sense folding, (c) force profile for equal-sense folding.

To verify the effect of curvature on the force required to fold the curved origami structure, we measured the folding force of the structure with five radii of curvature: 10, 11, 12.5, 14, and 15 mm. we tested both folding directions to show how they affect peak force in the folding direction. Fig. 24(a) shows the differences in peak force for equal-sense folding and opposite-sense folding in a specimen with a 10 mm radius of curvature. Fig. 24(b) and Fig. 24(c) show the relationship between curvature and force for equal-sense folding and opposite-sense folding. As curvature increases, the peak forces also increase. During folding the curved facets become flatter. Therefore, the facet of the more curved specimen needs more force to be folded.

3.5. Deployment Test

Rapid deployment involves fast phase changing from ballistic to gliding movements, and it is a major factor governing travel length. To evaluate deployment speed, the gliding module was hung on a stand and a video of its deployment was recorded at 120 frames per second. The average required time for deployment was 350 ms. Fig. 25 shows frames of this video.

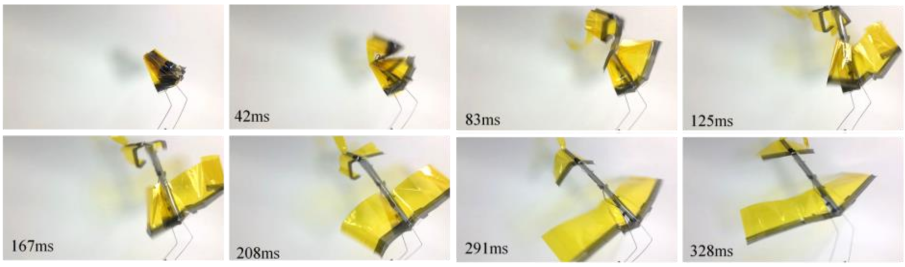


Fig. 25. Sequential stop-motion figures of deployment.

3.6. Gliding Test

The glider should not interrupt the jumping or ballistic performance of projectiles when the glider and jumping robot are integrated. One interruption factor is the drag caused by the area of the glider at takeoff and the upward ballistic phase. To verify how the gliding module affects ballistic motion, we tested three situations: The ballistic motion of a folded module without deploying, the projection of an initially unfolded gliding module, and initially folded module with deploying at highest point. We videotaped each motion and analyzed the trajectory of the module for each scenarios (Fig. 26).

Projection of the unfolded glider (Green marked scenario in Fig. 26) shows interrupted projection performance as a significant decrease of peak height, because of drag caused by initial large area of the glider wing. And the glider falls middle of the gliding. Owing to drag, the velocity is very low to generate lift force to keep gliding. But the fast transition to the gliding caused by no deploying process, makes it can travel farther than ballistic motion. In the initially folded and deploy at highest point glider case(red marked scenario in Fig. 26), the initially folded wing did not interrupt the peak height, and deployment makes it travel farther by start glide in the higher position than unfolded gliding. In 1 m up stepped launch, this experiment shows more than 2 m increase in x directional distance.

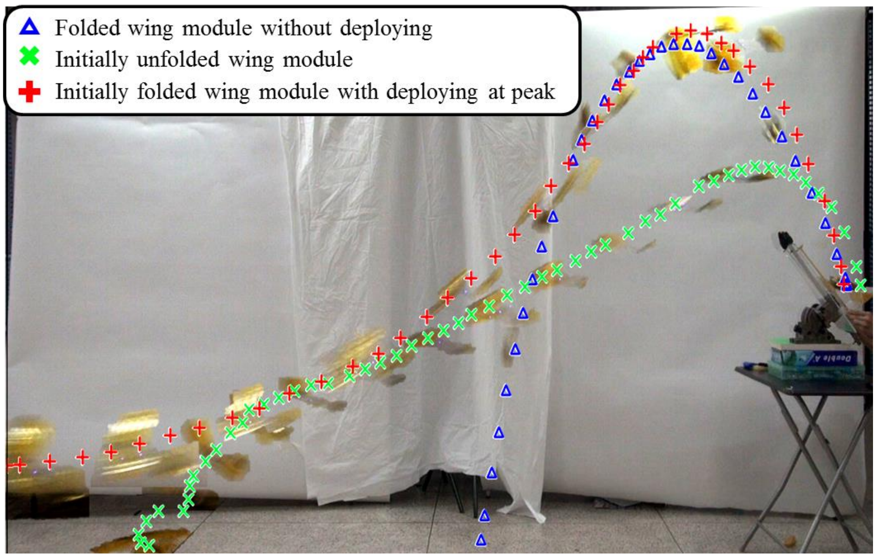


Fig. 26. Trajectory of the three different launches: folded wing module without deploying, initially deployed wing, and initially folded wing with deploying at peak height.

DISTRIBUTION A. Approved for public release: distribution unlimited.

III. Extra Activity Performances:

1. SNUMAX – Winner of RoboSoft Grand Challenge 2016

Fig. 27. 'SNUMAX' winner of *RoboSoft Grand Challenge 2016*

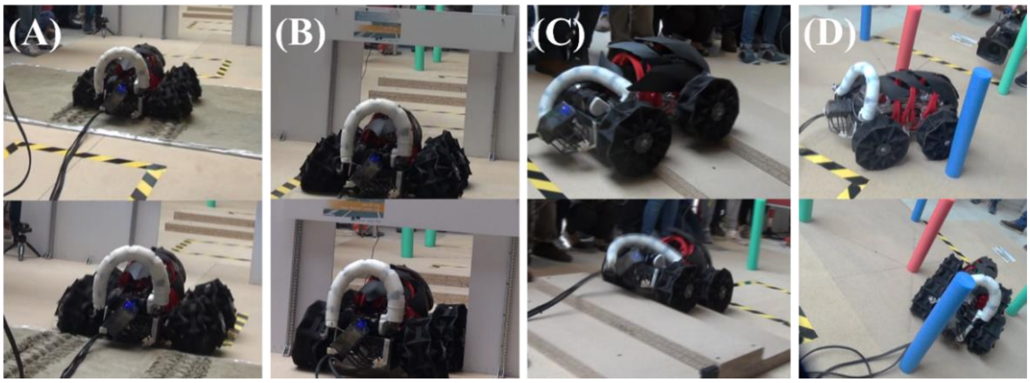


Fig. 28. Performance during the four terrestrial navigation scenario tasks. (A) Crossing sand terrain, (B) Passing through a small aperture, (C) Ascending and descending stairs, (D) Passing between unstable obstacles.

'SNUMAX' winner of *RoboSoft Grand Challenge 2016* shows a potential of the proposed wheel design (Fig. 27). *RoboSoft Grand Challenge* is the international competition for soft robot, which competes on the adaptability to the various environment. The origami-inspired transformable wheel allowed SNUMAX to accomplish the terrestrial scenario.

The wheel can assume two final configurations: wider along its axis with small diameter, and narrower along its axis with large diameter. Deformation of the wheel greatly increases maneuverability by enhancing the robot's adaptability to various types of terrain. By adjusting the diameter of the wheel, it is possible to adjust the wheel's shape and torque to achieve a balanced configuration that allows the robot to climb stairs and traverse rough terrain.

Fig. 28 shows various mission (A) Crossing sand terrain: Enlarging SNUMAX's wheels allowed it to overcome a small bump and move on sand terrain. (B) Passing through a small aperture: Shrinking SNUMAX's wheels allowed it to pass through a small aperture. (C) Ascending and descending stairs: Enlarging SNUMAX's wheels allowed it to ascend and descend stairs. (D) Passing between unstable obstacles: The robot was carefully maneuvered between unstable poles without touching them while narrowing the wheels.

2. Invited lecture in 2016 Korean Society of Mathematical Education annual symposium

Traditionally, paper folding is field of art, math, and education. Korean society of mathematical education has been tried to use a paper folding as an educational tool and held the workshop at 2016 annual symposium to present the possibility and potential of the paper folding. As the representative case of opening the paper folding application field in robotics, we were invited to organize the workshop.

The theme of the workshop is the paper-folding technique for robotics, and the workshop contains the presentation about our research performance (Fig. 29. [a]), the exhibition of SNUMAX' (Fig. 29. [b]), the hands-on activity of folding the deformable wheel (Fig. 29. [c], [d]). This event was our team's first activities for the public opened to high school students, teachers and school parents. Through the workshop, it was possible to know the public's think and desire on our research, and also arouse the interest of the public.

Fig. 29. (a) Presentation about the topic “Paper-folding Technique for Robotics” (b) Exhibition of SNUMAX, (c) Lecture about waterbomb pattern, (d) The hands-on activity of folding the deformable wheel.

List of Publications:

a) Papers published in peer-reviewed journals

[1] Jun-Young Lee, Brian Byunghyun Kang, Dae-Young Lee, Sang-Min Baek, Woong-Bae Kim, Woo-Young Choi, Jeong-Ryul Song, Hyeong-Joon Joo, Daegeun Park and Kyu-Jin Cho, “Development of a Multi-functional Soft Robot (SNUMAX) and Performance in RoboSoft Grand Challenge,” Front. Robot. AI, vol. 3, p. 63, 2016.

b) Papers published in peer-reviewed conference proceedings

[1] Sang-Min Baek, Dae-Young lee, Kyu-Jin Cho, "Curved Compliant Facet Origami-based Self-deployable Gliding Wing Module for Jump-gliding," in ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE, 2016.

[2] Sa-Reum Kim, Dae-Young Lee, Je-Sung Koh, and Kyu-Jin Cho, "Fast, Compact, and Lightweight Shape-Shifting System Composed of Distributed Self-Folding Origami Modules," in IEEE International Conference on Robotics and Automation (ICRA), 2016, pp. 4969-4974.

[3] Je-Sung Koh, Sa-Reum Kim and Kyu-Jin Cho, “Self-folding origami using the torsion shape memory alloy wire actuators”, in ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference IDETC/CIE, 2014.

[4] Dae-Young Lee, Ji-Suk Kim, Jae-Jun Park, Sa-Reum Kim and Kyu-Jin Cho, "Fabrication of Origami Wheel using Pattern Embedded Fabric and its Application to a Deformable Mobile Robot," IEEE International Conference on Robotics and Automation (ICRA), p. 2565, 2014

[5] Dae-Young Lee, Ji-Suk Kim, Sa-Reum Kim, Je-Sung Koh, Kyu-Jin Cho, “The Deformable Wheel Robot using Magic-Ball Origami Structure”, Proceedings of the ASME 2013 IDETC/CIE, 2013.

[6] Dae-Young Lee, Gwang-Pil Jung, Min-Ki. Sin, Sung-Hoon Ahn and Kyu-Jin Cho, “Deformable wheel robot based on origami structure," IEEE International Conference on Robotics and Automation (ICRA), pp. 5592-5597, 2013

c) Papers published in non-peer-reviewed journals and conference proceedings

[1] Sa-Reum Kim, Dae-Young Lee, Je-Sung Koh, and Kyujin Cho, "Development of a Physical 3-Dimensional Dot Module System Composed of Self-Folding Origami Modules", 2016 16th International Conference on Control, Automation and Systems (ICCAS 2016) Oct. 16-19, 2016 in HICO, Gyeongju, Korea

[2] Dae-Young Lee and Kyu-Jin Cho, "Design of Compliant Origami Structure for Deformable Wheel Mechanism," International Symposium on Green Manufacturing and Applications (ISGMA), Jun. 2014.

[3] Dae-Young Lee, Ji-Suk Kim, Sa-Reum Kim, Jae-Jun Park and Kyu-Jin Cho, “Design of Deformable-Wheeled Robot Based on Origami Structure with Shape Memory Alloy Coil Spring,” The 10th International Conference on Ubiquitous robots and Ambient Intelligence, Oct. 2013.

[4] Dae-Young Lee, Sa-reum Kim, Ji-Suk Kim, Jae-Jun Park and Kyu-Jin Cho, "Fabrication of Origami Structure using Pattern Enclosed Composite," 2013 13th International Conference on Control, Automation and Systems, Oct. 2013

d) Manuscripts submitted but not yet published

[1] Dae-Young Lee, Sa-Reum Kim, Ji-Suk Kim, Jae-Jun Park and Kyu-Jin Cho, “Origami Wheel Transformer: A Variable Diameter Wheel-Drive Robot Using an Origami Structure,” Softrobotics, submitted.